I.S., K. Petraki, A. Kusenko [arXiv: 1006.5458]

Collider signatures of sterile neutrinos in models with a gauge-singlet Higgs

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OUTLINE

- Singlet Higgs + sterile neutrino models have many motivations: neutrino masses, dark matter, baryogenesis.
- Bounds on the Higgs sector are relaxed compared to the SM.
- Revised branching ratios and decay modes for both Higgs particles.
- Collider signatures of sterile neutrino decays: missing energy, displaced vertices, lepton number violation.

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- While these states are introduced to explain neutrino masses, they can also explain dark matter for a range of parameters.

Seesaw mechanism

- With both Dirac and Majorana mass terms, neutrinos mix via:

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- But what's the origin of the new scale M_a?

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- If one imposes a Z_2 symmetry on the S boson, it can be a stable DM candidate, but no neutrino masses [Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy (2007)]

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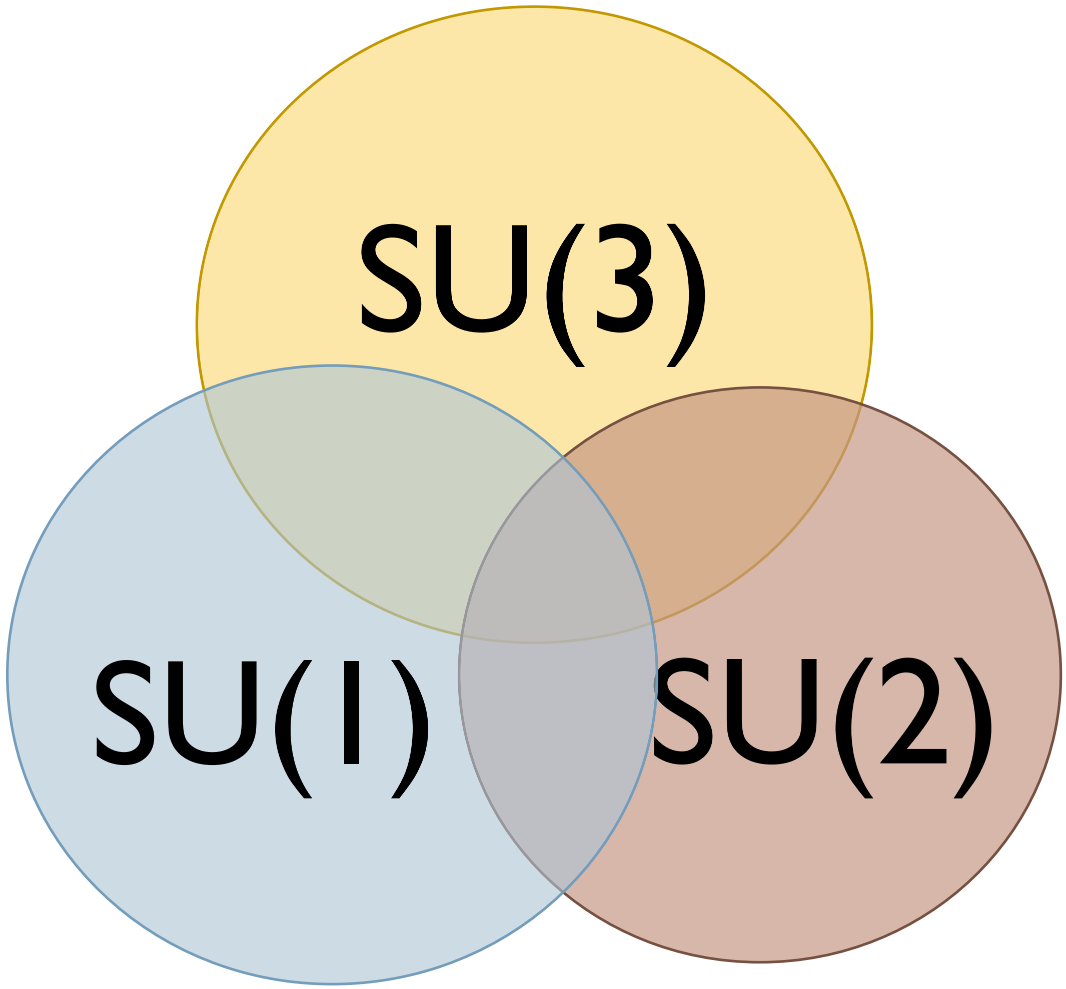
  - Same keV sterile neutrino can possibly explain pulsar kicks.
- DM keV neutrinos will not be produced at colliders.
- Is there any hope of finding sterile neutrinos at a collider?

How to produce sterile neutrinos at a collider

Gauge structure of the SM



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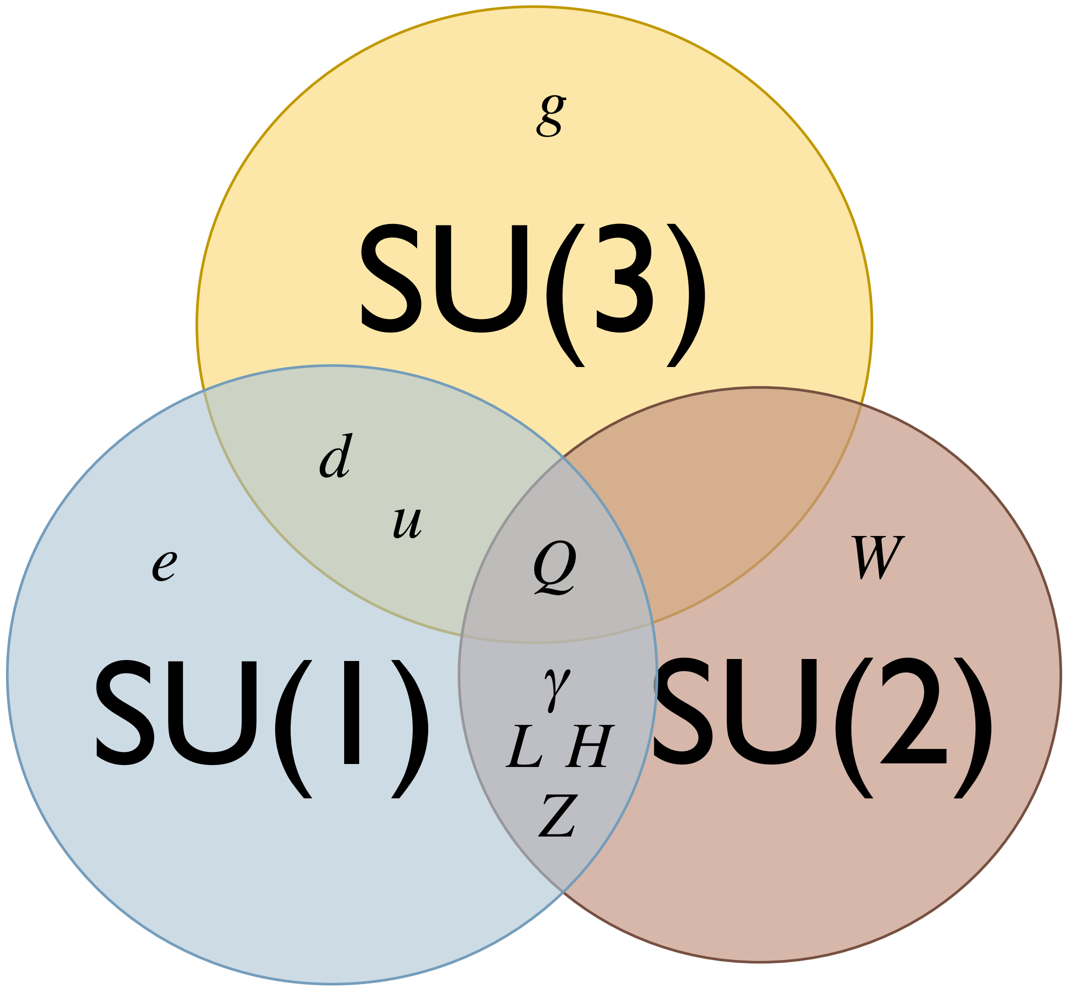

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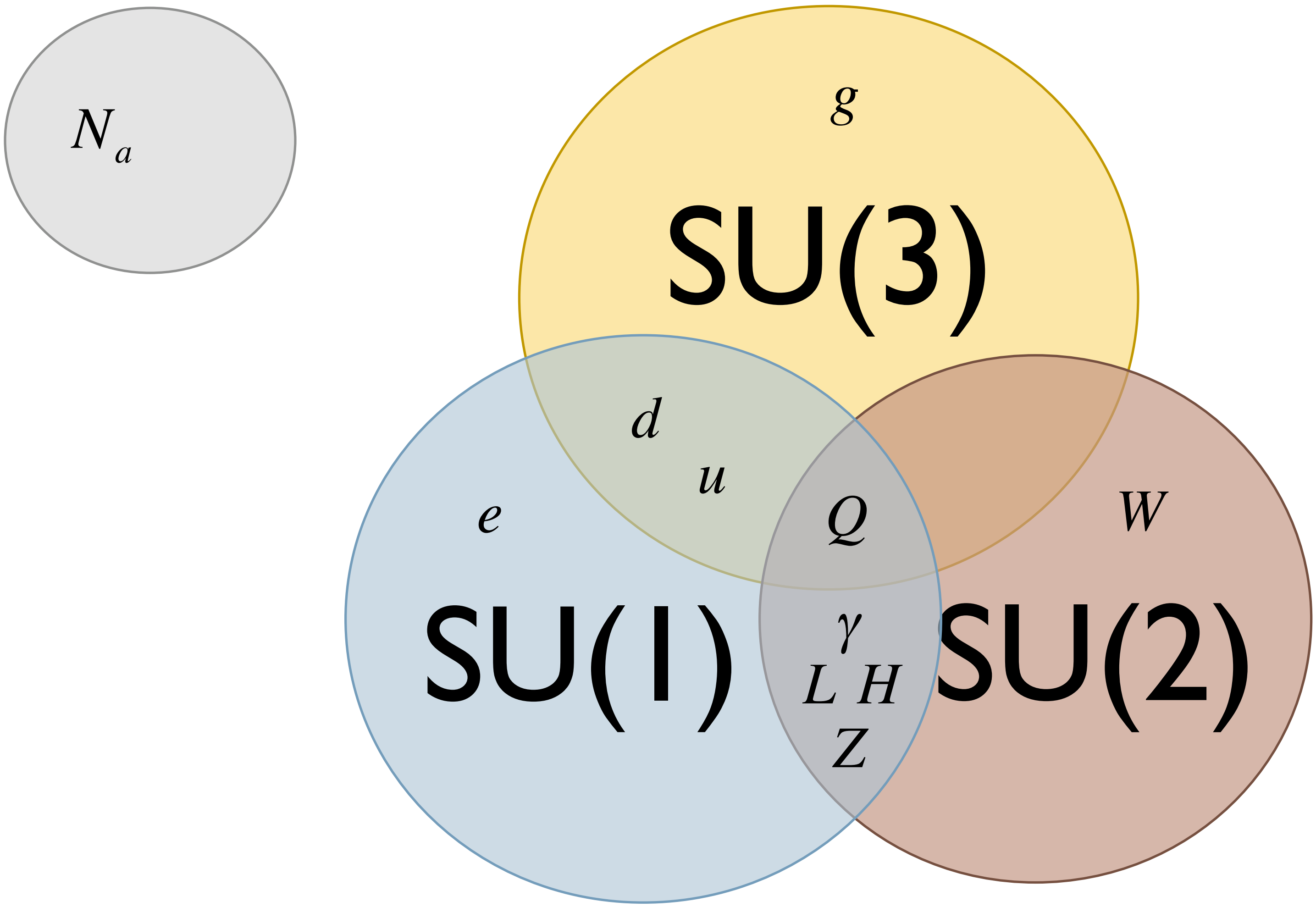

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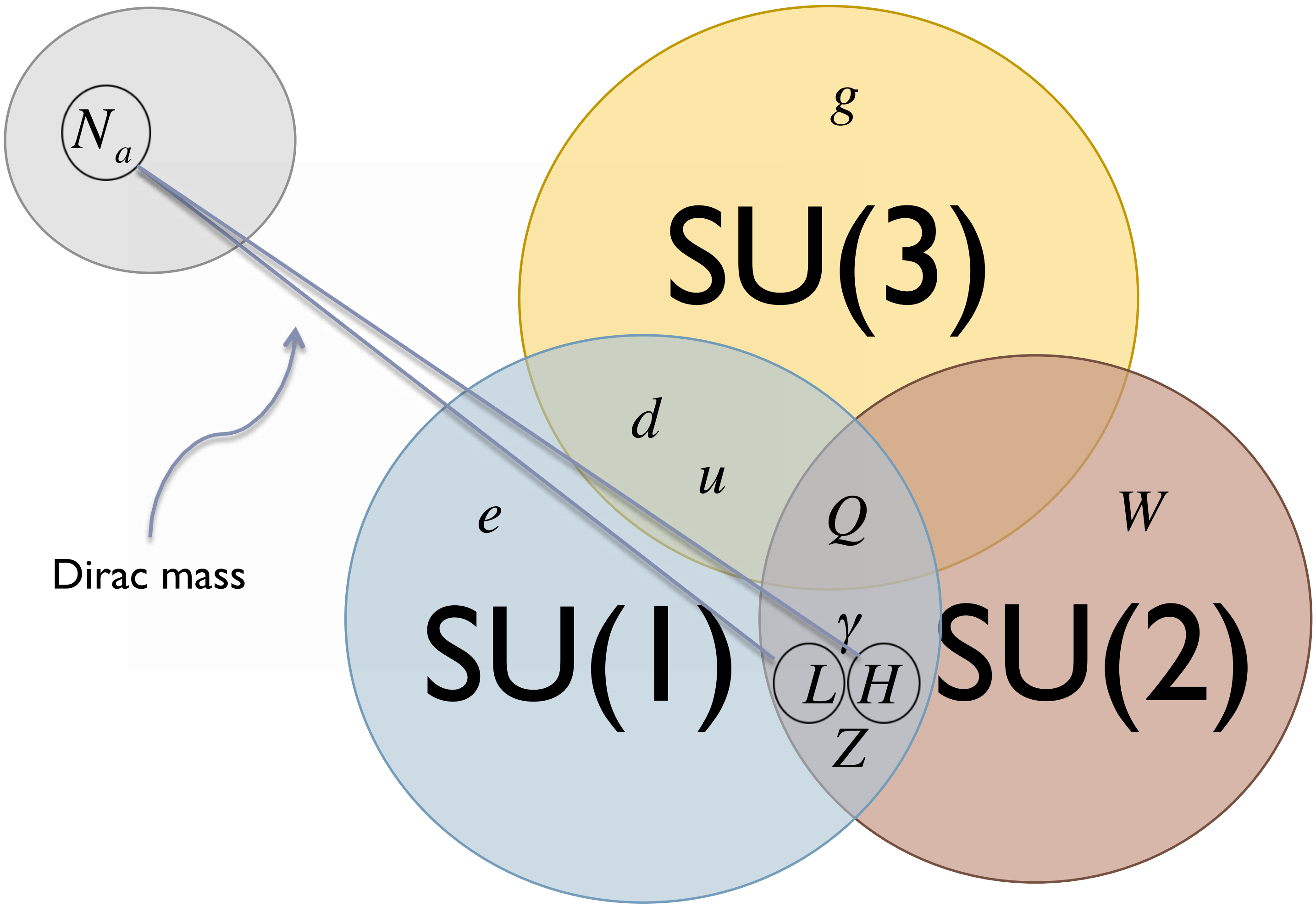

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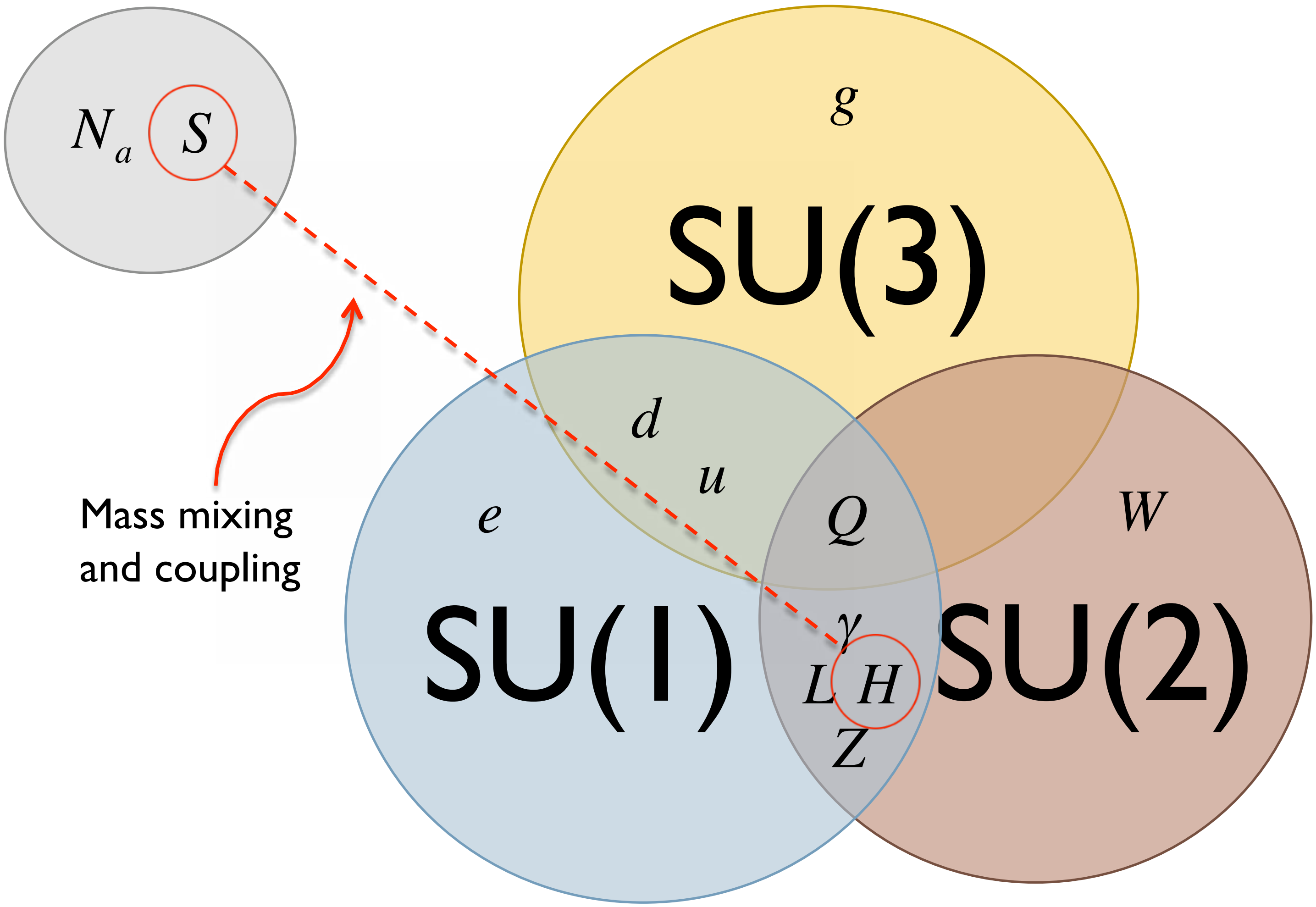

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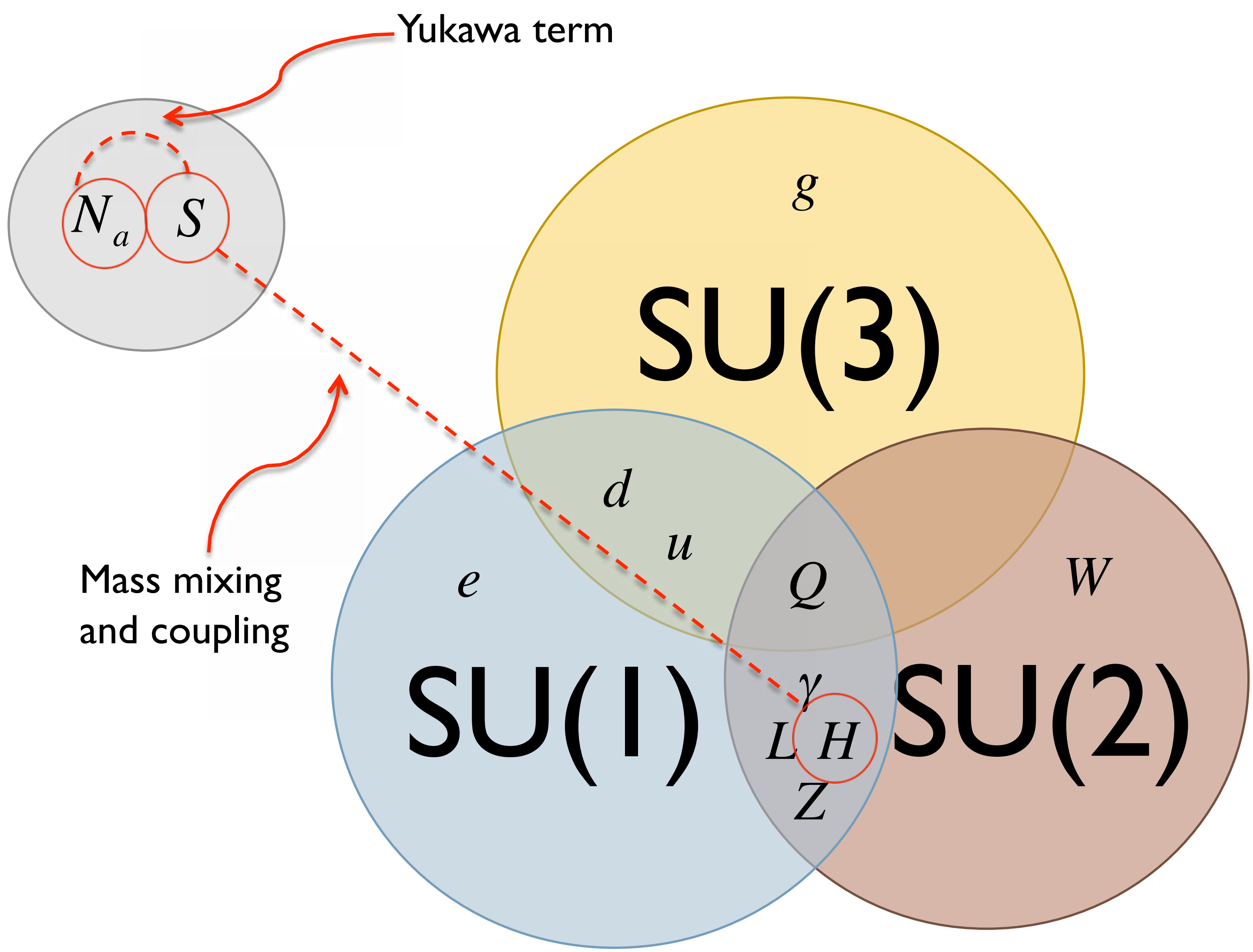

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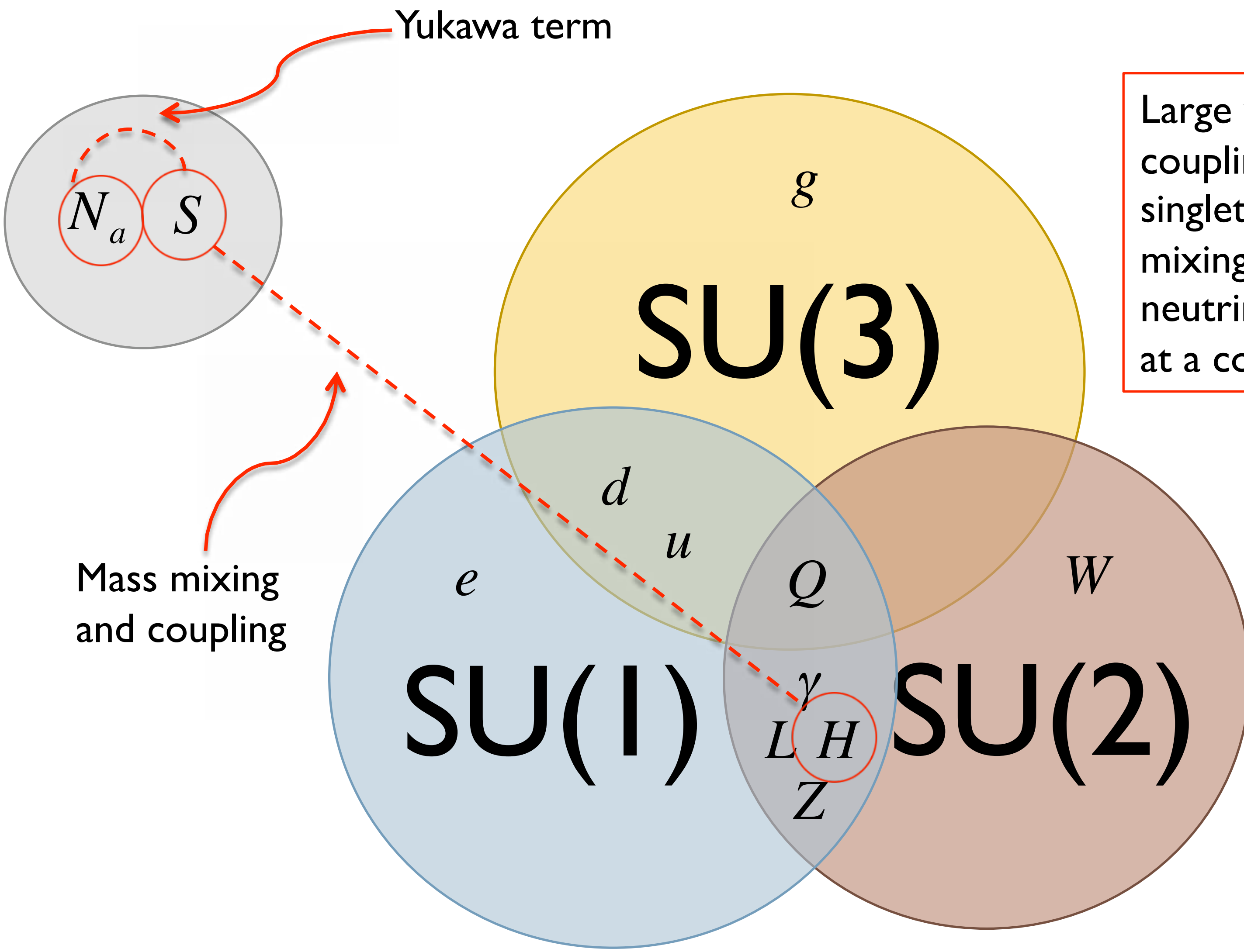

Large yukawa couplings + large singlet-doublet Higgs mixing = sterile neutrinos produced at a collider.

Relaxed constraints on the Higgs sector

- Higgs doublet-singlet mixing suppresses the gauge interactions of the Higgs's.
  - Reduced production cross section of the Higgs.
  - Reduced branching ratios to SM states.
- Branching ratios are further reduced due to the existence of new decays modes.

Higgs mixing and couplings

- Singlet and doublet Higgses mix:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} cos\phi_{HS} & sin\phi_{HS} \\ -sin\phi_{HS} & cos\phi_{HS} \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

- Where the mixing angle is determined by scalar potential.

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- We adopt the convention $M_{H_2} > M_{H_1}$
- The couplings to SM and sterile neutrinos now given by:

	Light Higgs (H_1)	Heavy Higgs (H_2)
Higgs-Neutrino coupling	$g_{1NN} = -if_a \sin\phi_{HS}$	$g_{2NN} = -if_a \cos\phi_{HS}$
Higgs-SM coupling	$g_{1SM} = g_{SM} \cos\phi_{HS}$	$g_{2SM} = g_{SM} \sin\phi_{HS}$

Mass mixing determines bounds

- (1) Small $\sin\phi_{HS}$: $H_1 \approx h,\ H_2 \approx S.$
  - Light Higgs is mostly doublet $\longrightarrow$ obeys SM LEP bound.
  - Heavy Higgs is mostly singlet $\longrightarrow$ weakened EWPO bound.
- (2) Maximal mixing: $H_{1,2} = \frac{1}{\sqrt{2}}(h \pm S).$
  - Light Higgs is mixed $\longrightarrow$ weakened LEP bound.
  - Heavy Higgs is mixed $\longrightarrow$ weakened EWPO bound.
- (3) Large $\sin\phi_{HS}$: $H_1 \approx S,\ H_2 \approx h.$
  - Light Higgs is mostly singlet $\longrightarrow$ weakened LEP bound.
  - Heavy Higgs is mostly doublet $\longrightarrow$ obeys SM EWPO bound.

Higgs branching fractions

- With modified Higgs-SM couplings and the introduction sterile neutrino mode, BR are altered as
  - Light Higgs:

$$Br(H_1 \to SM) = \frac{g_{1SM}^2 Br(h \to SM)\Gamma_{tot}^{SM}}{g_{1SM}^2 \Gamma_{tot}^{SM} + \Gamma(H_1 \to N_a N_a)}$$

  - Heavy Higgs:

$$Br(H_2 \to SM) = \frac{g_{1SM}^2 Br(h \to SM)\Gamma_{tot}^{SM}}{g_{1SM}^2 \Gamma_{tot}^{SM} + \Gamma(H_2 \to N_a N_a) + \Gamma(H_2 \to H_1 H_1)}$$

Higgs branching ratios

- We can relate the new branching ratios to the SM values:

$$Br(H_i \to X_j X_j) = \frac{Br_j^{SM}}{1 + A_i}$$

$$A_1 = \frac{\Gamma(H_1 \to NN)}{\cos^2\phi \ \Gamma_{tot}^{SM}}, \qquad A_2 = \frac{\Gamma(H_2 \to NN) + \Gamma(H_2 \to 2H_1)}{\sin^2\phi \ \Gamma_{tot}^{SM}}.$$

- While non-SM channels have

$$Br(H_i \to non - SM) = \frac{A_i}{1 + A_i}.$$

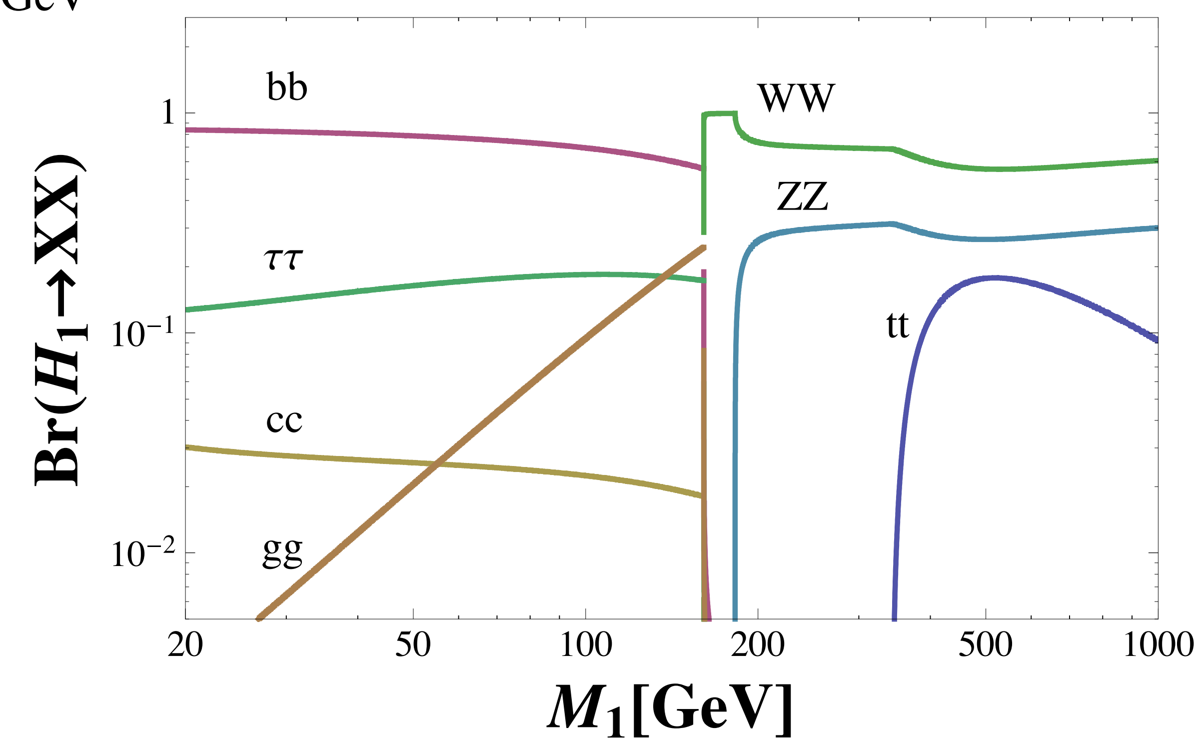
- Thus in the limit that $A_i << 1$ the Higgs becomes SM-like.

H_1

$$H_1 \approx h$$

$\sin\phi = 0.01$

$M_N = 20$ GeV

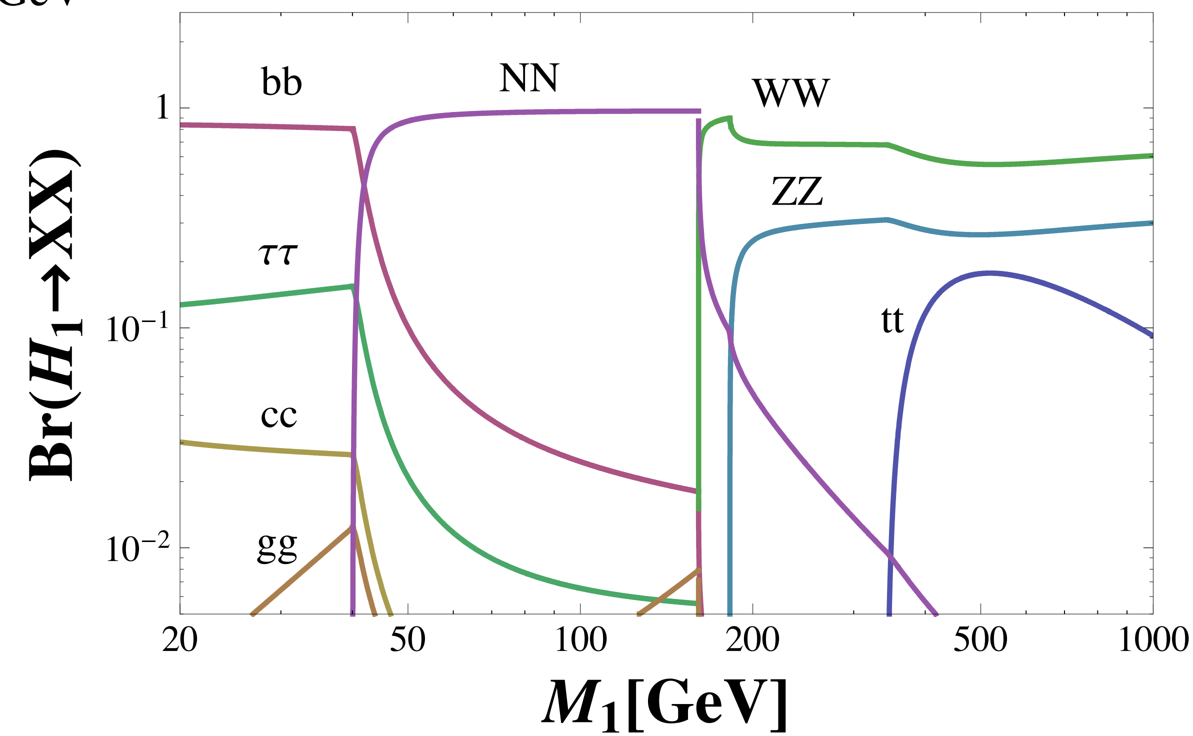


H_1

$$H_1 \approx 2^{-1/2}(h+S)$$

$\sin\phi = 1/\sqrt{2}$

$M_N = 20$ GeV



H_1

$H_1 \approx S$

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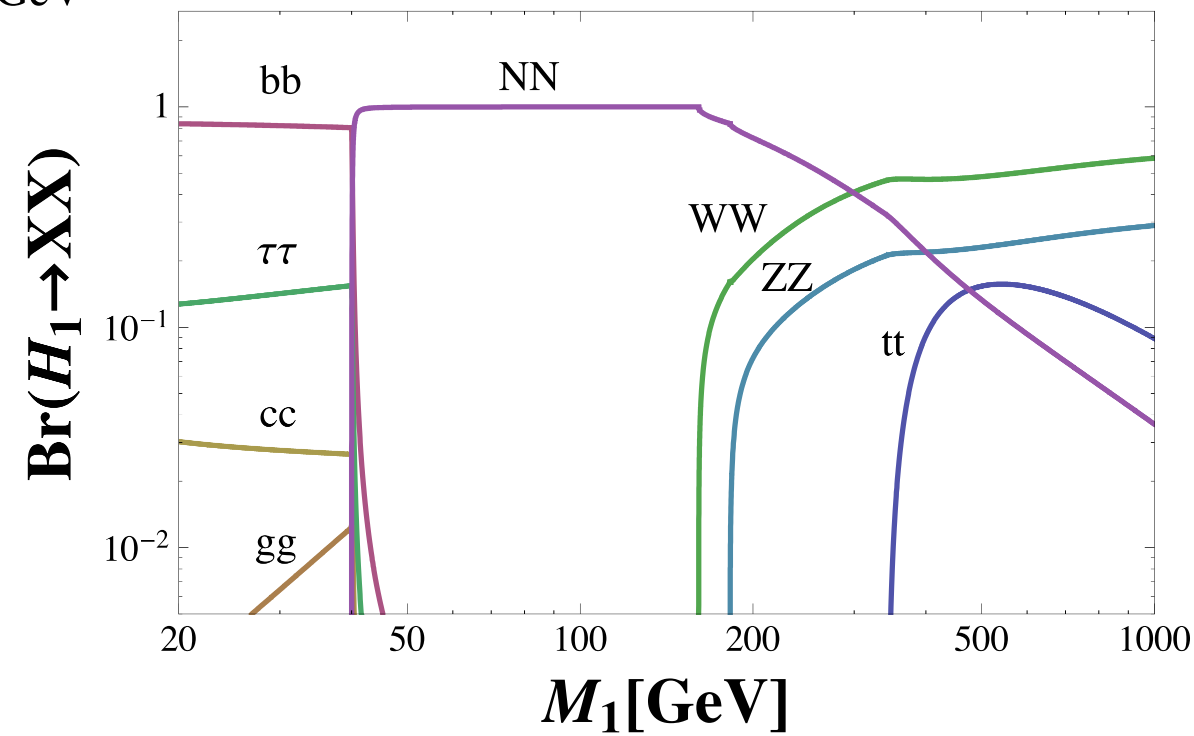
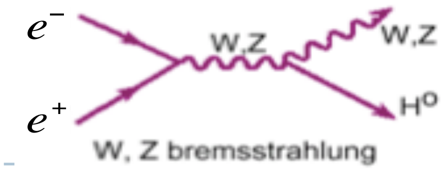


Imposing LEP constraints

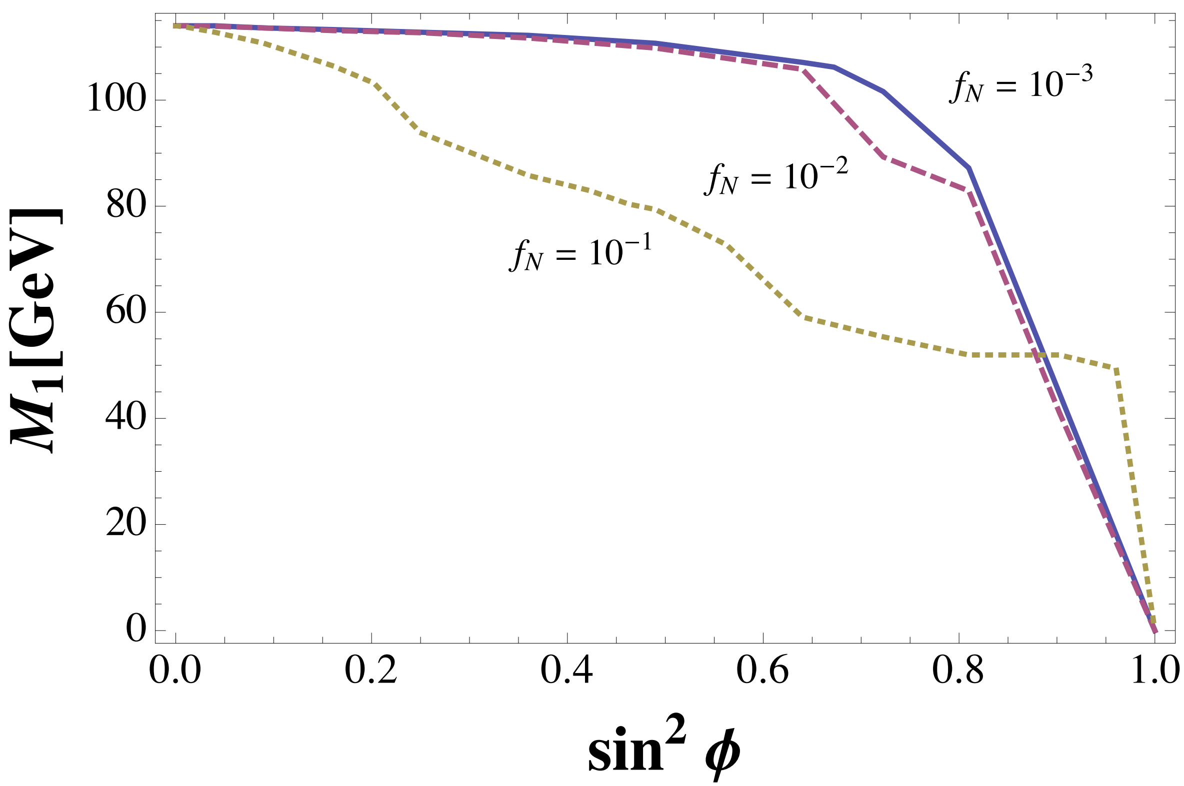


- A SM Higgs is ruled out at 95% CL for $M_h < 114.4\text{GeV}$.
  - Assumes SM production cross section and SM branching ratios.
- However LEP has non-SM bounds, constrained by the parameter:

$$\xi^2(H_i \to X_{SM}) = \left(\frac{\sigma(e^+e^- \to ZH_i)}{\sigma(e^+e^- \to Zh_{SM})}\right) \times \frac{Br(H_i \to X_{SM})}{Br(h_{SM} \to X_{SM})}$$

- Reduced HZZ coupling and/or reduced SM branching fractions weakens the LEP bound.

Lower bound on H_1 mass

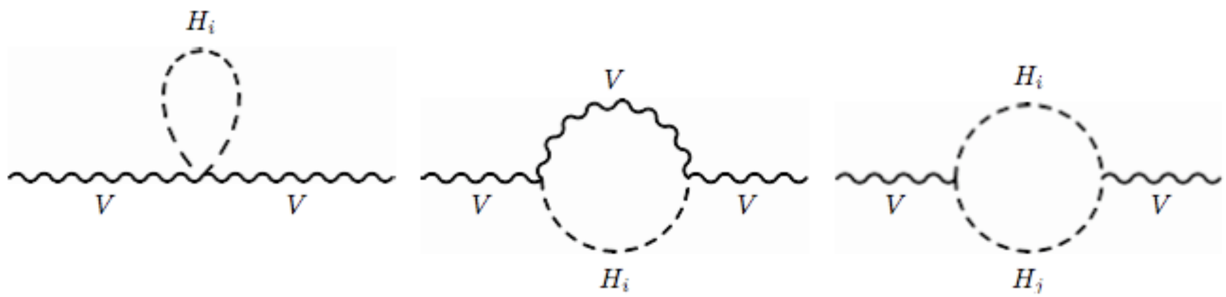


$\langle S \rangle = 200$ GeV

As the mixing increases the light Higgs becomes dominantly singlet, and decouples from the SM.

As the Yukawa coupling increases, the branching fraction to NN increases, reducing SM Br's.

Electroweak precision observable (EWPO) bounds



[Barger et al. (2007), Profumo, Ramsey-Musolf, Shaughnessy (2007)]

- Radiative corrections to the W and Z boson propagators from the scalar sector imply a weakening of EWPO constraints.
- Maximal mixing reduces the EWPO upper bound on the heaviest Higgs to $M_{H_2} \leq 220\text{GeV}$.
- Dominant radiative corrections come from Higgs sector.

Modified Higgs bounds

	Model A	Model B	Model C
$\sin\phi$	$1/\sqrt{2}$	0.01	0.99
Higgs states	$H_{1,2} = \frac{1}{\sqrt{2}}(h \pm s)$	$H_1 \approx h,\ H_2 \approx s$	$H_1 \approx s,\ H_2 \approx h$
LEP constraints	$M_{1,2} \geqslant 80$ GeV	$M_{1,2} \geqslant 114$ GeV	$M_2 \geqslant 114$ GeV
EWPO constraints	$M_{1,2} \leqslant 220$ GeV	$M_1 \leqslant 185$ GeV	$M_{1,2} \leqslant 185$ GeV

Decays of the sterile neutrino

Graesser [0705.2190], Graesser [0704.0438], Gorubov, Shaposhnikov [0705.1729].

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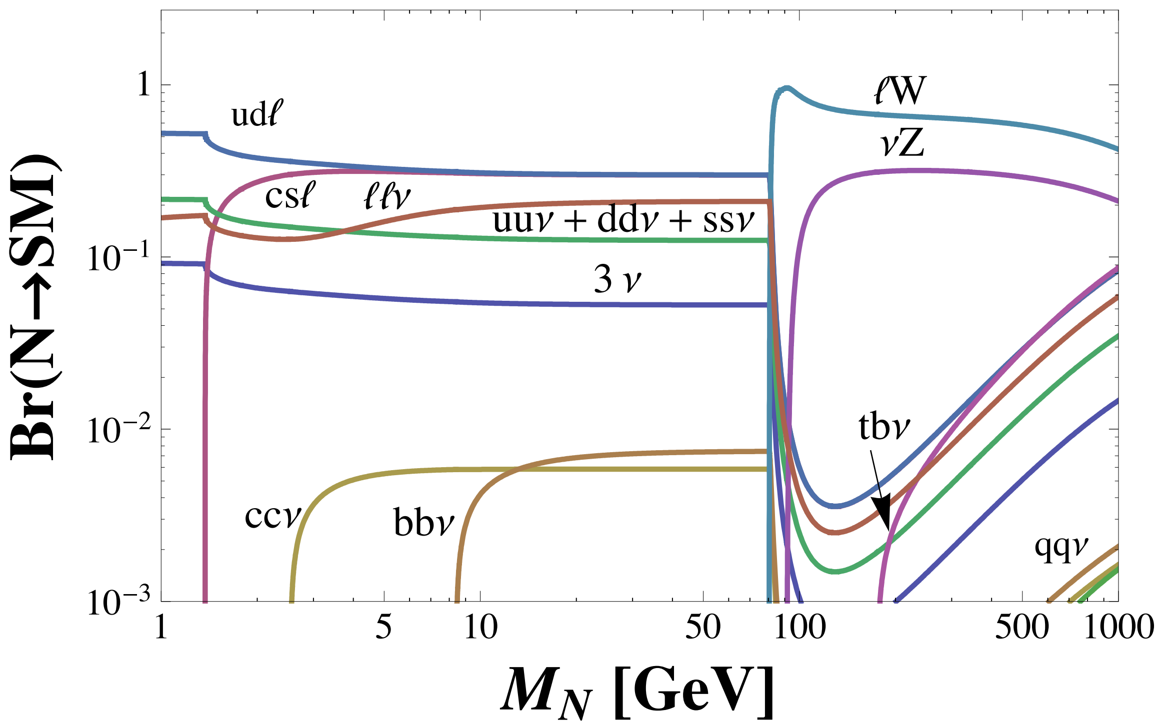
- Each decay produces odd number of leptons.

Sterile neutrino decays



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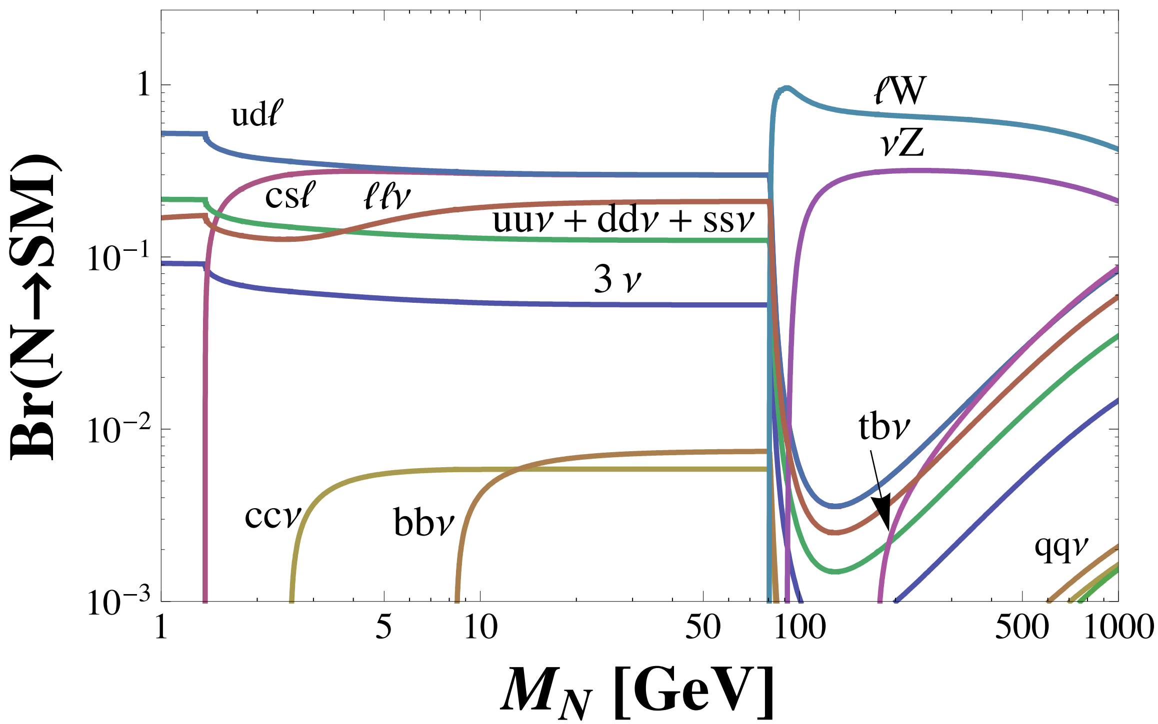

Light steriles dominantly decay into (light quarks + charged lepton) and (two charged leptons + missing energy).

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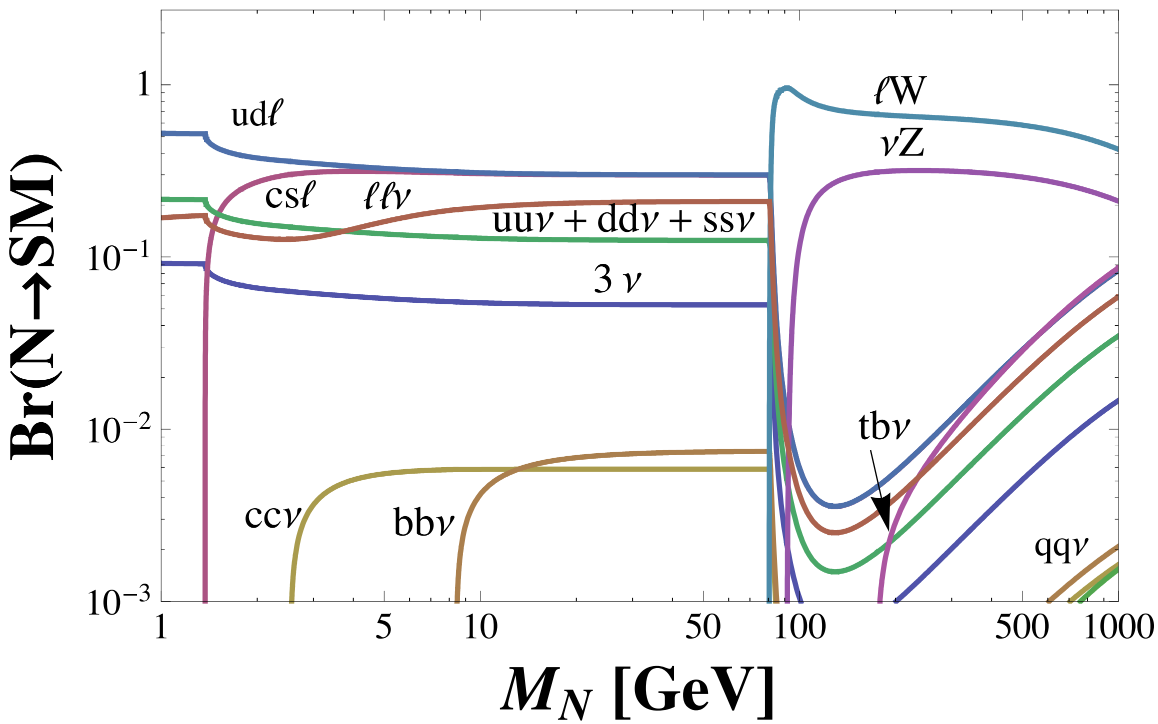
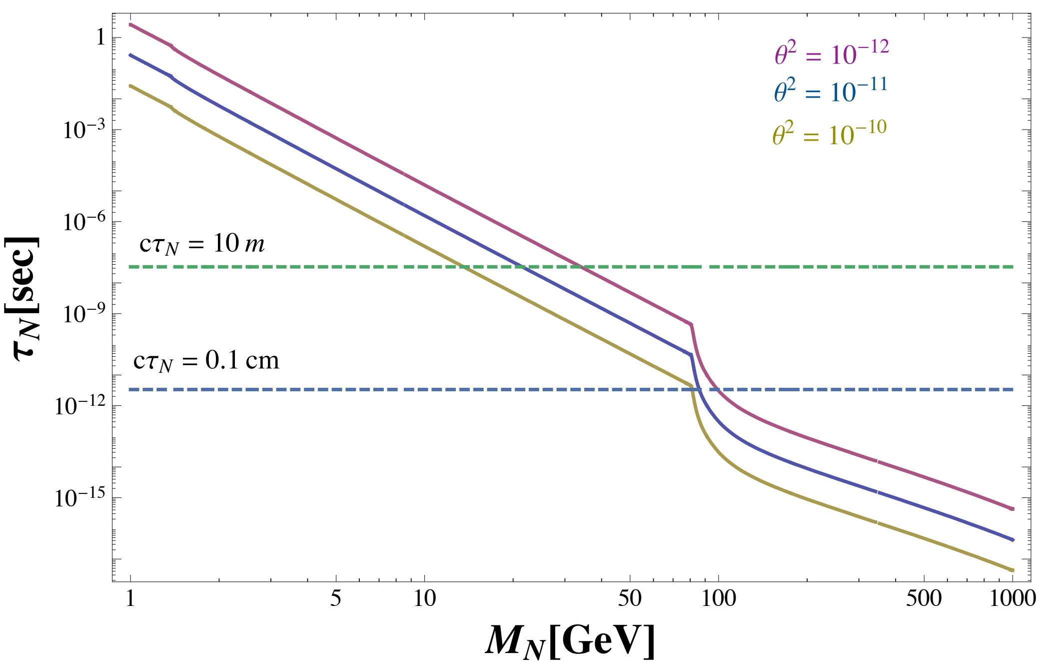


Light steriles dominantly decay into (light quarks + charged lepton) and (two charged leptons + missing energy).

Heavy steriles decay mostly into (charged lepton + W boson) or (Z + missing energy).

Displaced vertices



Intermediate neutrino masses

$$21\ \mathrm{GeV}\left(\frac{10^{-11}}{\sin^2\theta}\right)^{1/5} \leq M_N \leq 86\ \mathrm{GeV}\left(\frac{10^{-11}}{\sin^2\theta}\right)^{1/5}$$

decay displaced from production region.

Light neutrinos appear as missing energy

$$qq \to qqVV \to qqH \to qq + \text{inv}$$

- Neutrinos with $\leq 15\text{GeV}$ decay decay outside the detector, and appear as missing energy.
- Discoverability of invisibly decaying Higgs assessed in [Eboli, Zeppenfield (2000)].
- When $Br(H_i \to N_2 N_2) \approx 100\%$, and the Higgs is produced via weak boson fusion appropriate cuts on the correlation of the forward jets allow for a 5σ detection .

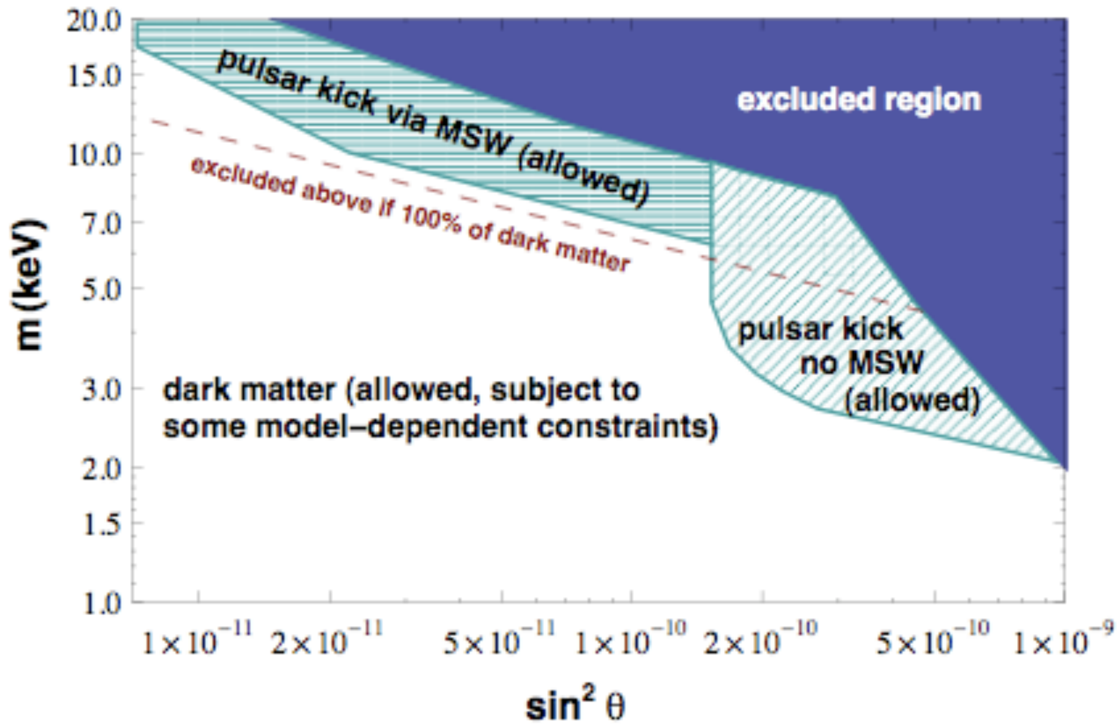
Summary

- Extended singlet sector relaxes both direct LEP and indirect EWPO bounds on Higgs masses.
  - Viable models have large NN branching fractions.

- Collider signatures depend on the sterile neutrino mass:
  - Light neutrinos appear as missing energy.
  - Intermediate neutrinos decay with macroscopically displaced vertex with lepton number violation.
  - Heavy neutrinos decay promptly with lepton number violation.

Extra slides

Sterile DM bounds



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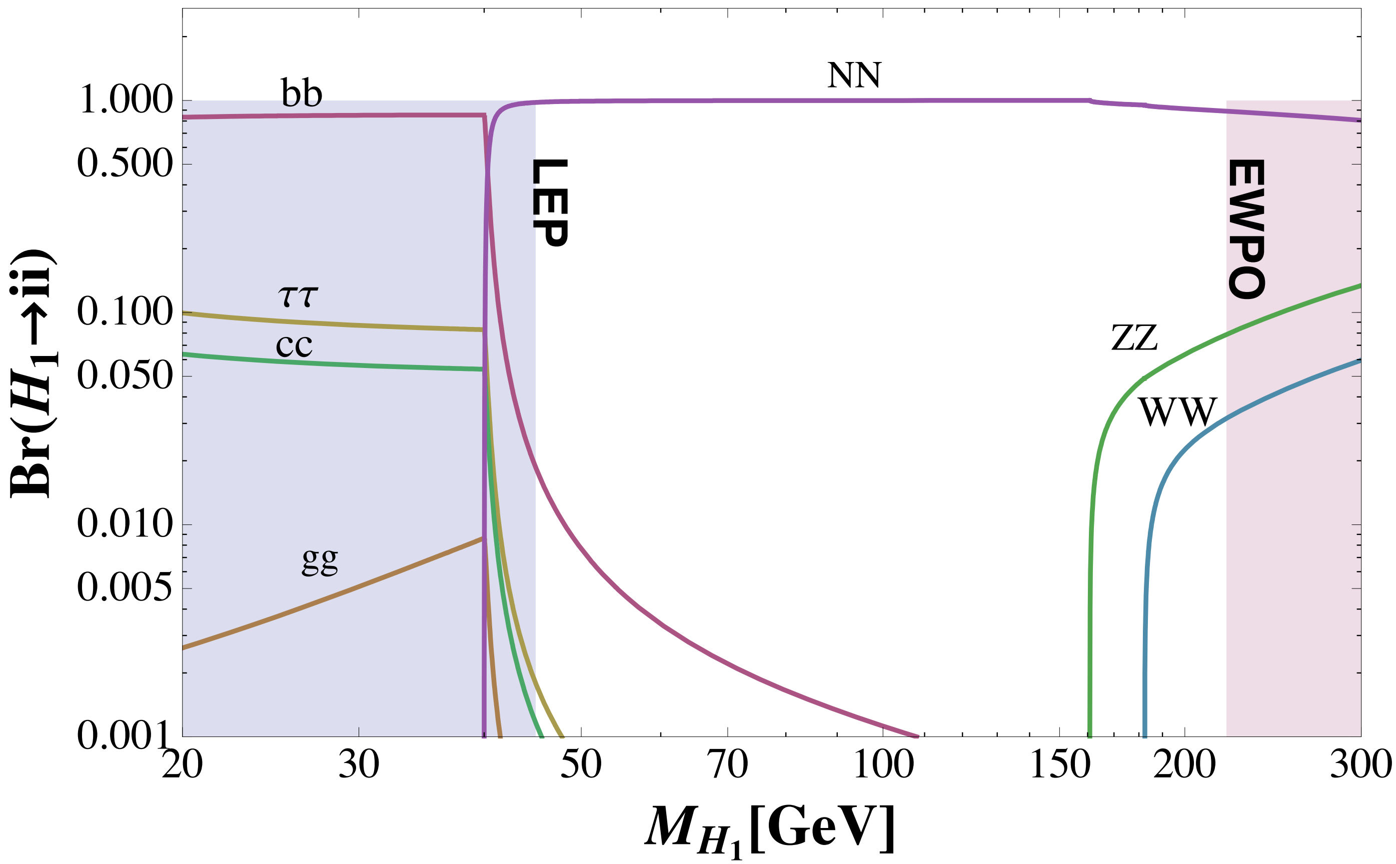
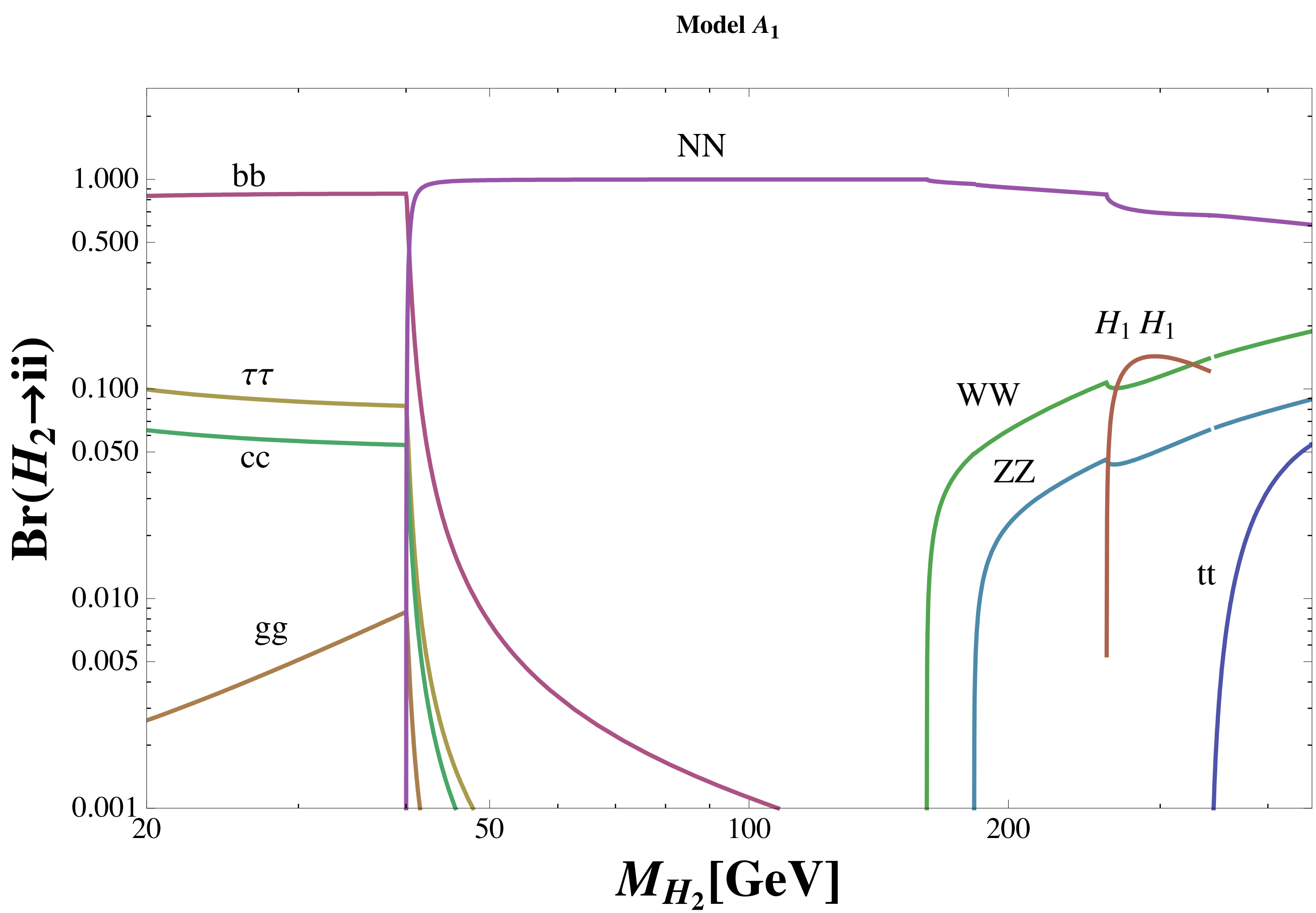
- Singlet Higgs allows for the possibility of a 1st order phase transition, making EW baryogenesis possible [Petraki, Kusenko (2008)].
- Neutrinos have mass.

Light Higgs branching ratios

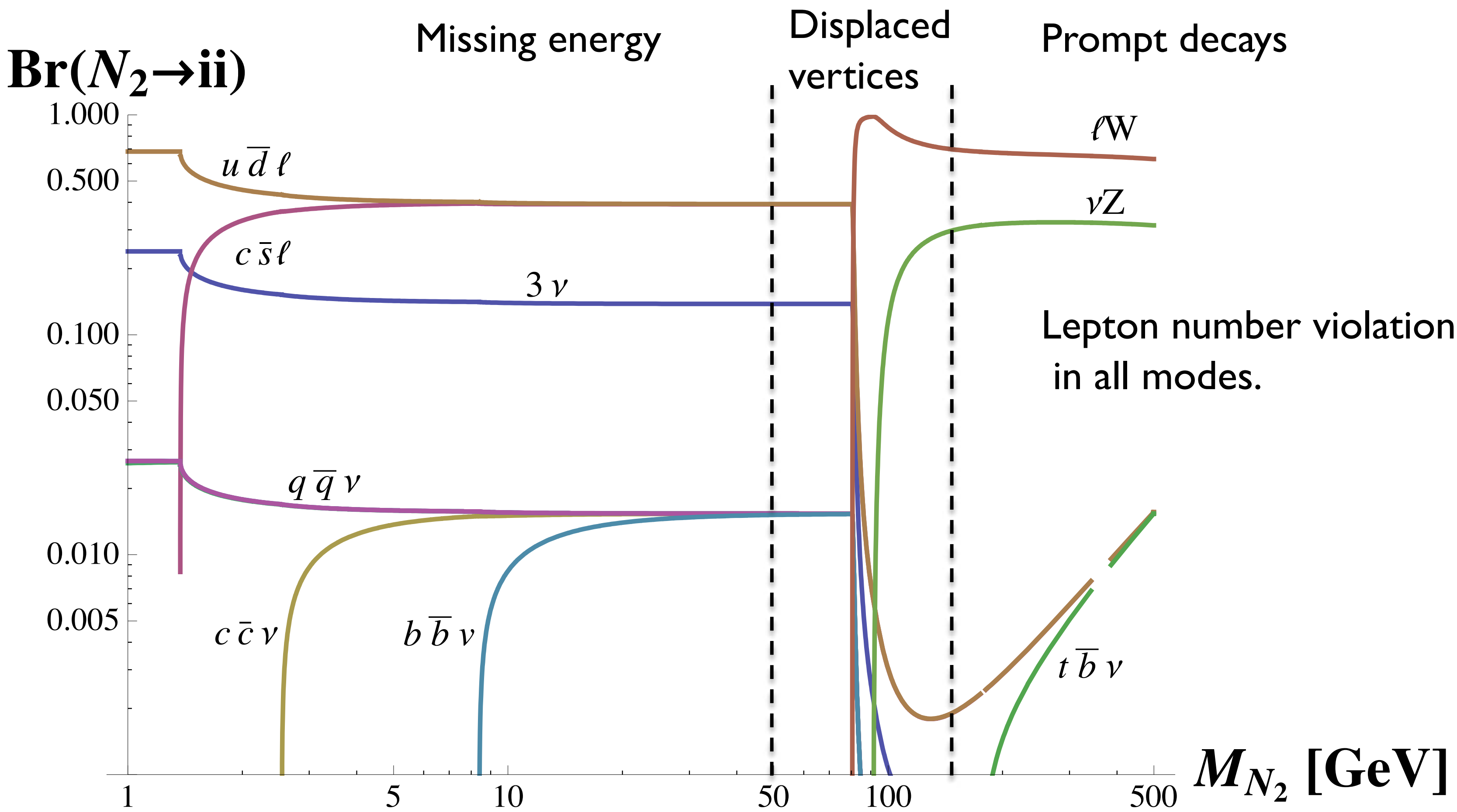
$$\sin\phi_{HS} = 1/\sqrt{2} \qquad M_{N_2} = 20GeV \qquad \langle S \rangle = 200\text{GeV}$$



Heavy higgs decays



Sterile neutrino decays

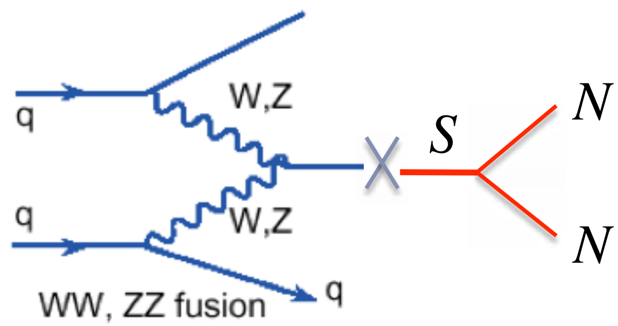


Extended Higgs sector

- The real singlet field has mass mixings and couplings to SM Higgs:

$$V(H,S) = -\frac{1}{2} m_S^2 S^2 - m_H^2 |H|^2 + \frac{1}{6}\alpha S^3 + \omega |H|^2 S + \lambda_H |H|^4$$
$$+ \frac{1}{4}\lambda_S S^4 + 2\lambda_{HS} |H|^2 S^2$$

- For example:



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$$L \supset \frac{f_a}{2} S \overline{N}_a^c N_a + \text{h.c.} \quad \Rightarrow \quad M_a = f_a \langle S \rangle$$

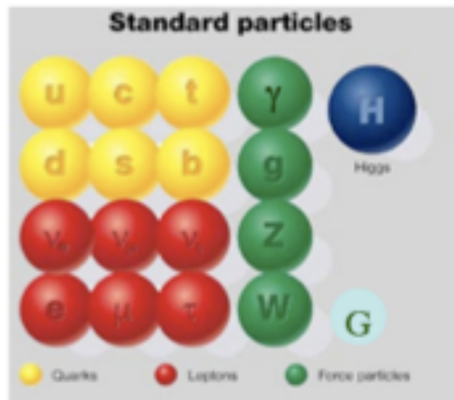
- Most general potential (assuming no new symmetries):

$$V(H,S) = -\frac{1}{2} m_S^2 S^2 - m_H^2 |H|^2 + \frac{1}{6} \alpha S^3 + \omega |H|^2 S + \lambda_H |H|^4 + \frac{1}{4} \lambda_S S^4 + 2\lambda_{HS} |H|^2 S^2$$

- Kusenko (2006) has shown that a keV sterile neutrino can be DM and explain pulsar kicks.
- Petraki and Kusenko (2008) have shown that S decays can be dominant production mechanism of DM and the presence of S allows for a 1st order EWPT.

Review

- Constraints on the Higgs boson properties from the hep-ph/9703412



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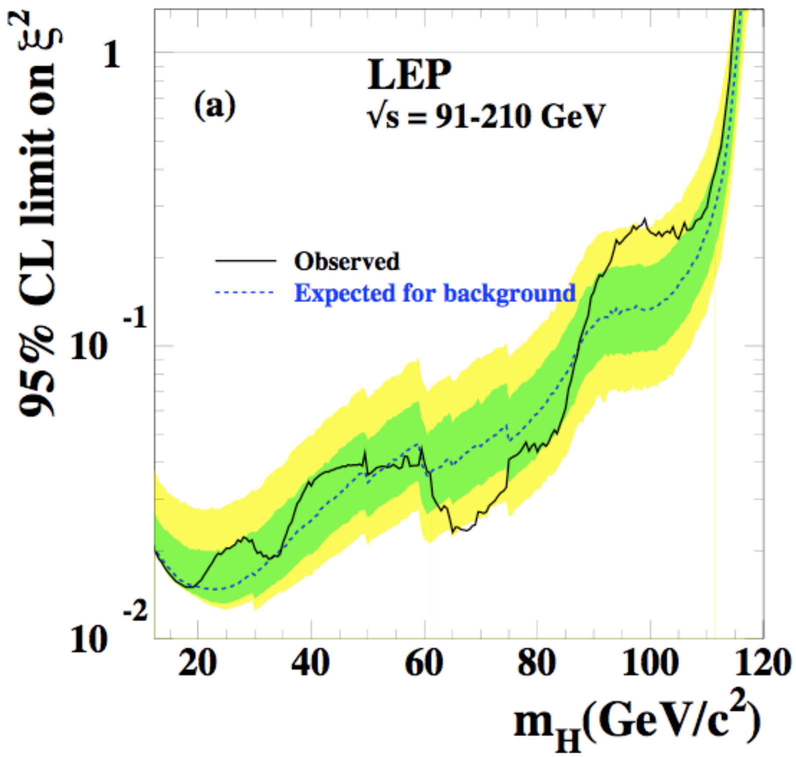
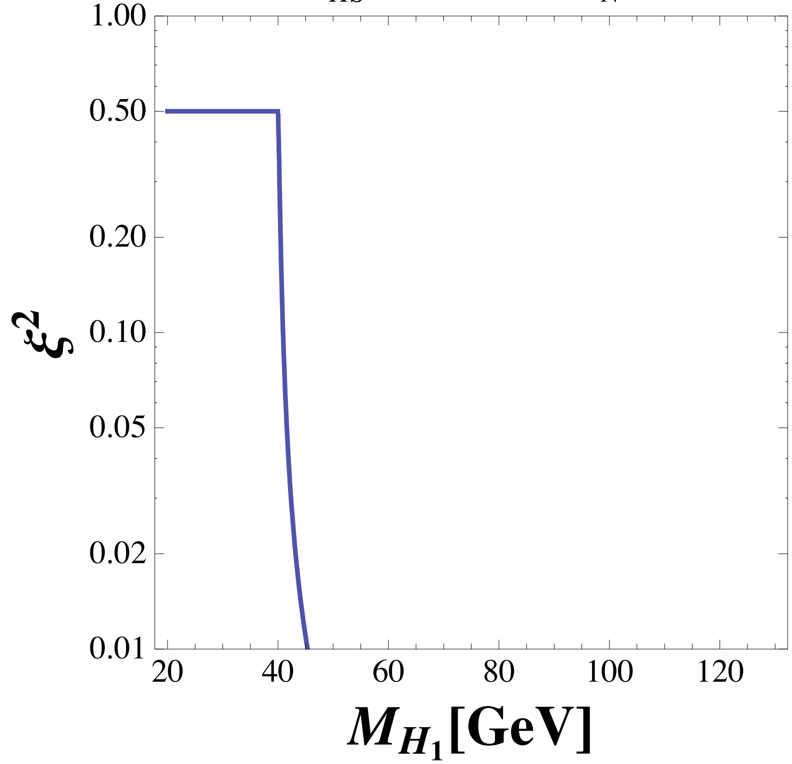
- Thus active and sterile neutrinos mass mix via:

$$\hat{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_a \end{pmatrix}$$

LEP bounds are generically relaxed



$\sin\phi_{HS} = 1/\sqrt{2},\ M_N = 20GeV$



Maximal mixing reduces LEP bound to $M_{H_1} \sim 45\text{GeV}$

Displaced vertices

Intermediate neutrino masses $50GeV \leq M_{N_2} \leq 150GeV$ decay displaced from production region.